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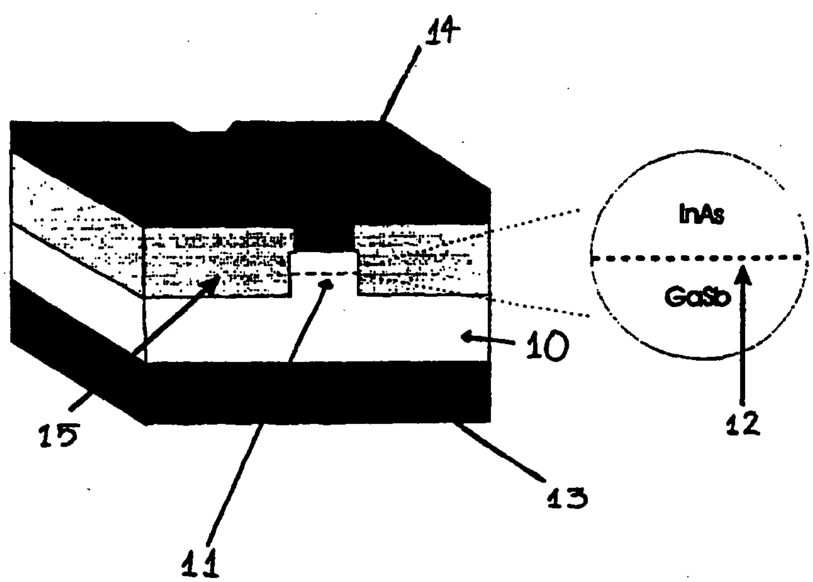

(57) Abstract

The infrared radiation source consists of a layer of GaSb (10) and a layer of InAs (11) which meet at an interface region (12) consisting of either GaAs or InSb. The two layers define a broken bandgap at the interface (12) and on application of a forward bias by means of contacts (13, 14) infrared radiation is produced at the interface. The interface exhibits negative differential resistance on application of a biasing voltage and the wavelength of the radiation is tunable in dependence on the size of the biasing voltage.

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INFRARED RADIATION SOURCE

The present invention relates to an infrared radiation source and in particular to a source of incoherent or coherent infrared radiation which can be tuned for wavelengths between approximately 1 and 10 μm.

Currently there are very few sources of infrared radiation in the wavelength range 1 to 10 μm. The available sources include large mainframe CO and CO_2 lasers and very specialised lower power semiconductor devices such as the Quantum Cascade Laser (QCL) of Bell Laboratories (Faist et al, Science vol. 264, p553 (1994)) which requires great semiconductor growth control. The tuneability of these sources is negligible and the sources are costly to produce. More recently investigations have been made into the possibility of generating electroluminescence in III-V semiconductor heterojunctions. These investigations have suggested that radiative recombination is also possible where the junction has a staggered bandgap, i.e where there is partial overlap in the bandgaps of the semiconductor materials either side of the junction.

In US 5588015 a semiconductor laser is described in which layers of InAs and GaSb are used to define quantum well regions bounded on each side by barrier layers of AlSb and outer cladding layers. The barrier layers act to artificially alter the quantum well confinement in the InAs and GaSb layers to form 'square' quantum wells. With this structure, on application of a biasing voltage electrons tunnel from the cladding layer to the ground state of the conduction band of the InAs but are then prevented from tunnelling further as the layer of GaSb is sufficiently thick to block direct tunnelling to the second cladding layer. The electrons therefore relax to the ground state of the valence band of the GaSb which relaxation results in the emission of electromagnetic radiation. The emission wavelength can be altered through adjustment of the thicknesses of the InAs and GaSb layers. This means though that once the structure has been made the emission wavelength cannot be altered.

The present invention seeks to provide a new source of infrared radiation which is tuneable and is suited for use in a wide range of applications.

In a first aspect the present invention provides an infrared radiation source comprising a first layer of GaSb p type semiconductor material or an alloy thereof meeting a second layer of InAs n type semiconductor material or an alloy thereof at an interface region and forward biasing means for applying a forward biasing voltage across the interface region.

In an alternative aspect the present invention provides an infrared radiation source comprising a first layer of GaSb p type semiconductor material or an alloy thereof meeting a second layer of InAs n type semiconductor material or an alloy thereof at an interface region which interface region has an average thickness of not more than 2 nm and biasing means for applying a biasing voltage across the interface region, whereby radiative recombination occurs in the interface region when a forward bias is applied.

With the present invention varying the forward bias applied across the interface region alters the emission wavelength and permits tuning of the radiation source.

The interface region consists of either GaAs or InSb having an average thickness of 2 nm or less. Ideally, the interface region is a monolayer of either GaAs or InSb. Furthermore, in the absence of a forward bias a broken bandgap is formed at the interface region between the first and second layers and a negative differential resistance is exhibited in response to the application of a forward bias.

Preferably, the biasing means is in the form of paired metal Ohmic contacts for applying a biasing voltage across the interface region of between 0.1 and 5 V. The radiation source may include optical confinement means for the generation of coherent radiation. The optical confinement means may be in the form of outer semiconductor layers outside of the first and second layers, the outer semiconductor layers

having a refractive index less than the refractive index of the first and second layers thereby providing optical confinement to radiation generated at the interface region. A buffer layer may be provided to improve lattice matching.

The infrared radiation source may comprise a double semiconductor heterojunction having a third semiconductor layer opposite the interface region which is either of GaSb p type material or of InAs n type material.

In a further embodiment a quantum cascade laser is provided comprising a plurality of stacked radiation sources in accordance with the present invention.

Embodiments of the present invention will now be described by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a tuneable IR radiation source in accordance with the present invention;

Figures 2a and 2b are energy bandgap diagrams of a radiation source in accordance with the present invention;

Figures 3a and 3b are schematic diagrams of the layers of an IR radiation source incorporating optical confinement in accordance with the present invention;

Figures 4a and 4b are energy bandgap diagrams respectively for p-n-p and n-p-n double heterojunctions in accordance with the present invention;

Figure 5 is an energy bandgap diagram for a single stage quantum casade laser; and

Figure 6 is an energy band diagram for a multi-stage quantum cascade laser.

With reference to Figure 1 the basic structure of an infrared radiation source is shown schematically. The structure consists of a semiconductor p-n heterojunction. In this case the layer 10 of p type material is GaSb and the layer 11 of n type material is InAs. The semiconductor materials meet at an interface 12 which is preferably 2 nm

or less in thickness and is ideally a monolayer of either GaAs or InSb . The rest of the structure of the radiation source is conventional and consists of metal Ohmic contacts 13, 14 in electrical contact with each of the semiconductor layers 10, 11 respectively to enable a forward bias to be applied across the interface 12 and an insulator 15 either side of the interface 12.

In use, a forward bias is applied across the interface of the source which generates infrared (IR) radiation emission from the interface, parallel to the plane of the interface. Preferably, the forward bias is less than 3 V, for example 0.1 to 3 V, with a current density of around 0.2-20×10^4 Acm $^{-2}$ which increases with bias above the bias of the NDR region (described below). The wavelength of the IR radiation emitted is in the range 1 to 10 μm and the wavelength can be altered by means of a bias adjusting device by varying the size of the forward bias applied to the heterojunction. The wavelength is continuously variable or tuneable across the range of wavelengths, although in a laser it would hop between the modes of the optical confinement cavity. The emitted light may be continuous but is preferably pulsed. The efficiency of the electroluminescence is greater at a forward bias in excess of the range of bias at which NDR is observed. The source is operational generally at atmospheric pressure, in air and at a reduced temperature, for example 77K. It is anticipated that operation at room temperature will also be achieved.

Analysis of the characteristics of the radiation source described above has shown that negative differential resistance (NDR) is exhibited during the application of forward bias across the interface region, with the NDR strengthening with decreasing temperature. NDR is identified by a semimetal to semiconductor transition (SMSCT) at a critical bias: Figure 2a shows the semimetallic state at zero bias and Figure 2b shows the semiconducting state at a bias above the critical bias. NDR is easily identified by a decrease in current with respect to increasing bias.

From Figure 2a it can be seen that the InAs/GaSb structure

has a broken energy bandgap at zero bias. In other words the type II energy band alignment at the interface results in the valence band of GaSb being an energy Δ above the conduction band of InAs. It is believed that this structure results in the formation of a two dimensional electron gas (2DEG) in the InAs and a two dimensional hole gas (2DHG) in the GaSb either side of the interface. When a forward bias is applied across the interface, in Figure 2b a forward bias of v=300 mV is shown, recombination of electrons from the 2DEG with holes from the 2DHG results in radiation in the wavelength range 1 to 10 μm. The confinement energies of the 2DEG and 2DHG increase with the applied bias thereby increasing the limits of the photon energy range and decreasing the corresponding emission wavelengths. In this way the emission wavelengths of the source can be tuned through variation of the applied bias.

As may be clearly seen from Figure 2a, 'triangular' quantum wells are formed in each of the layers as a result of the charge distribution at the interface. The radiation source is fabricated to permit these 'triangular' quantum wells to form.

The p and n type layers are grown using conventional vapour deposition (MOVPE) techniques at atmospheric or low pressure to ensure high quality epitaxial layers. Each of the layers is formed in turn with no additional separate barreir layer being formed between the p and n layers. Instead, the MOVPE technique is used to ensure the average thickness of the interface layer 11 can be made less than 2 nm and to enable biased growth at the interface to control whether the interface is GaAs-like or InSb -like, through use of appropriate termination layers. Alternative techniques, for example MBE (molecular beam epitaxy) may also be used. The contacts are formed preferably employing conventional sputtering techniques.

Emission from the top of the structure is possible by leaving a hole in the metal contact 14 to the n type layer 11. A circular mesa structure in which a ring metal contact is provided on the top of the n type layer and insulator wholly surrounds the sides of the interface and the n

type layer so that radiation can only be emitted through the ring contact, is convenient where incoherent radiation is desired.

Where the exposed end facets of the structure shown in Figure 1 are plane and parallel, tuneable coherent radiation is emitted from the interface at high enough currents. The applied current necessary to achieve laser action can be reduced through the introduction of highly reflective metal or dielectric layer coatings on the facets or by using an external cavity. In addition highly doped layers having a lower refractive index are provided either side of the n and p layers. As shown in Figure 3a, a first confinement strain-symmetrised superlattice (SS-SL) layer 16 of p^+-GaAlSb/InAs is provided adjacent the p layer 10 and a second confinement SS-SL layer 17 of n^--GaAlSb/InAs is provided adjacent the n layer 11. Each of these confinement layers has a lower refractive index than the refractive indexes of the n and p layers. This provides optical confinement to radiation generated at the interface, where the separation L between the two confinement layers is around 0.5-3 μm depending on whether the laser is optimised to operate at shorter or longer wavelengths. A further layer of p type material 18 is provided outside of the first confinement layer 16 and a further layer of n type material 19 is provided outside of the second confinement layer 17 respectively to establish good epitaxial growth and to aid the fabrication of a good electrical contact to the aluminium bearing layer. The choice of material for the low refractive index layers will depend on the substrate and buffer layer used. For example AlAsSb alloy or a AlAs/AlSb SS-SL could be used for these layers in an inverted device grown on a substrate or relaxed buffer layer of InAs as shown in Figure 3b. Alternatively, reflective quarter wave stacks could be provided of suitable semiconductor material for vertical laser emission.

The quality of the contact with the structure is important in ensuring reliable electroluminescence. However, conventional procedures for forming the contact may be employed. In the case of the structures shown in Figures 3a and 3b a highly doped thick (~20nm) layer may be provided on the top of the structure to improve the contacting process. In

particular, it is desired that the contacts are stable under the higher current densities used in a laser.

Although the structure of the radiation source described above involves a single heterojunction, other structures having more than one junction can be provided and can be useful in addressing problems such as the strain due to the slightly different lattice parameters of the two semiconductor materials. For example double heterojunctions can be employed to address problems associated with lattice strain. In turn this enables the active lasing interface to be located about the peak of the optical field established by the low refractive index confinement layers. As shown in Figure 4a a double heterojunction may consist of a layer 20 of p type material (GaSb) followed by a layer 21 of n type material (InAs) followed by a further layer 22 of p type material (GaSb). The first interface 23 between layers 20 and 21 is passive whereas the second interface 24 between layers 21 and 22 is active, i.e. radiation emitting. In Figure 4b the alternative double heterojunction structure is shown in which a layer 25 of GaSb is sandwiched between outer layers of InAs 26, 27. With this structure it is the first interface 28 which is active with the second interface 29 being passive. This arrangement of the various p and n type layers is preferred because it is easier to make reliable electrical contacts to the outer layers as InAs has a low contact resistance and is suited to the high current densities required for laser operation. To assist in identifying the broken energy gap of these structures in the Figures, filled states in the conduction band of the InAs layers are shaded dark grey whilst empty states in the valence band of the GaSb layers are shaded light grey. To reduce the effects of lattice mismatch preferably the central layer 21 or 25 is only around 10-100 nm thick. As is usually the case, the substrate, not shown, is preferably the same as the outer (cladding) layers or has a relaxed buffer layer of the same material. The double heterojunction structures are less susceptible to degradation through dislocation movement, and so it is expected that they will exhibit longer operational lifetimes than the single heterojunction.

The use of strained layers at the interface such as p-InGaSb between the interface and GaSb or n-InAsSb between the interface and InAs can also be used to alter the wavelength range of the source and could improve the overall efficiency of the radiation source.

As shown in Figures 4a and 4b the outer layers of the double heterojunction are the same polarity. This makes it easier to form the metal Ohmic contacts to the outer layers and also makes the radiation source particularly suited to use in multiple stage structures. In Figure 5a the energy bands for a triple heterojunction or a single stage quantum cascade laser are shown with a five stage version of the cascade laser shown in Figure 6. In Figure 6 there are five active interfaces but only the first is indicated. A multi-stage cascade laser has the advantage that more light is generated within the optical confinement region which in turn makes the laser more powerful and more efficient. The working voltage for a N-stage device is approximately N times that for a single stage device operating at the same wavelength. The size of the operating voltage and the heat generated at the passive interfaces thus limits the number of stages. The thickness of the confinement region or the strain in the multi-stage region (if not grown under strain symmetrised conditions by careful design of the buffer layer) also limits the total number of stages of the cascade laser to the extent that the individual thicknesses of the layers become increasingly small for increasing numbers of layers.

It should be noted that for the sake of clarity the lower refractive index layers necessary for laser operation have been omitted from Figures 4, 5 and 6.

It will of course be apparent that alterations to the various arrangement of layers described and the introduction of further intermediate layers for the purposes of lattice matching, for example could also be provided.

The IR radiation source described above, has a number of applications not least in communications where there is a transmission window in the atmosphere in the 3-5 and 10 μm regions. This means the

radiation source is suited for use in local communications and remote control and guidance in both military and civilian applications. Also, many polluting molecules such as methane and other car exhaust components have absorption bands in the 3-10 μm wavelength region which means the source can be used to identify the presence of these pollutants. Also, as the IR radiation source is tuneable, different pollutants can be separately identified using the same monitoring device.

CLAIMS

1. An infrared radiation source comprising a first layer of GaSb p type semiconductor material or an alloy thereof meeting a second layer of InAs n type semiconductor material or an alloy thereof at an interface region and forward biasing means for applying a forward biasing voltage across the interface region.

2. An infrared radiation source comprising a first layer of GaSb p type semiconductor material or an alloy thereof meeting a second layer of InAs n type semiconductor material or an alloy thereof at an interface region which interface region has an average thickness of not more than 2 nm and biasing means for applying a biasing voltage across the interface region, whereby radiative recombination occurs in the interface region when a forward bias is applied.

3. An infrared radiation source as claimed in either of claims 1 or 2, further including a bias adjusting device for altering the voltage of the bias applied across the interface region whereby the wavelength of emitted radiation may be altered.

4. An infrared radiation source as claimed in claim 1, wherein the interface region consists of either GaAs or InSb.

5. An infrared radiation source as claimed in claim 4, wherein the interface region is a monolayer of either GaAs or InSb.

6. An infrared radiation source as claimed in any one of the preceding claims, wherein the biasing means consists of paired metal Ohmic contacts for applying a biasing voltage across the interface region of between 0.1 and 5 V.

7. An infrared radiation source as claimed in any one of the preceeding claims, further including optical confinement means are provided for the generation of coherent radiation.

8. An infrared radiation source as claimed in claim 7, wherein the optical confinement means consists of outer semiconductor layers outside of the first and second layers, the outer semiconductor layers having a refractive index less than the refractive index of the first and second layers.

9. An infrared radiation source as claimed in any one of the preceding claims, further including at least one buffer layer to improve lattice matching.

10. An infrared radiation source as claimed in any one of the preceding claims, further including a third semiconductor layer opposite the interface region consisting of either GaSb p type material or InAs n type material thereby forming a double semiconductor heterojunction.

11. A quantum cascade laser comprising a plurality of stacked infrared radiation sources in accordance with any one of the preceding claims.

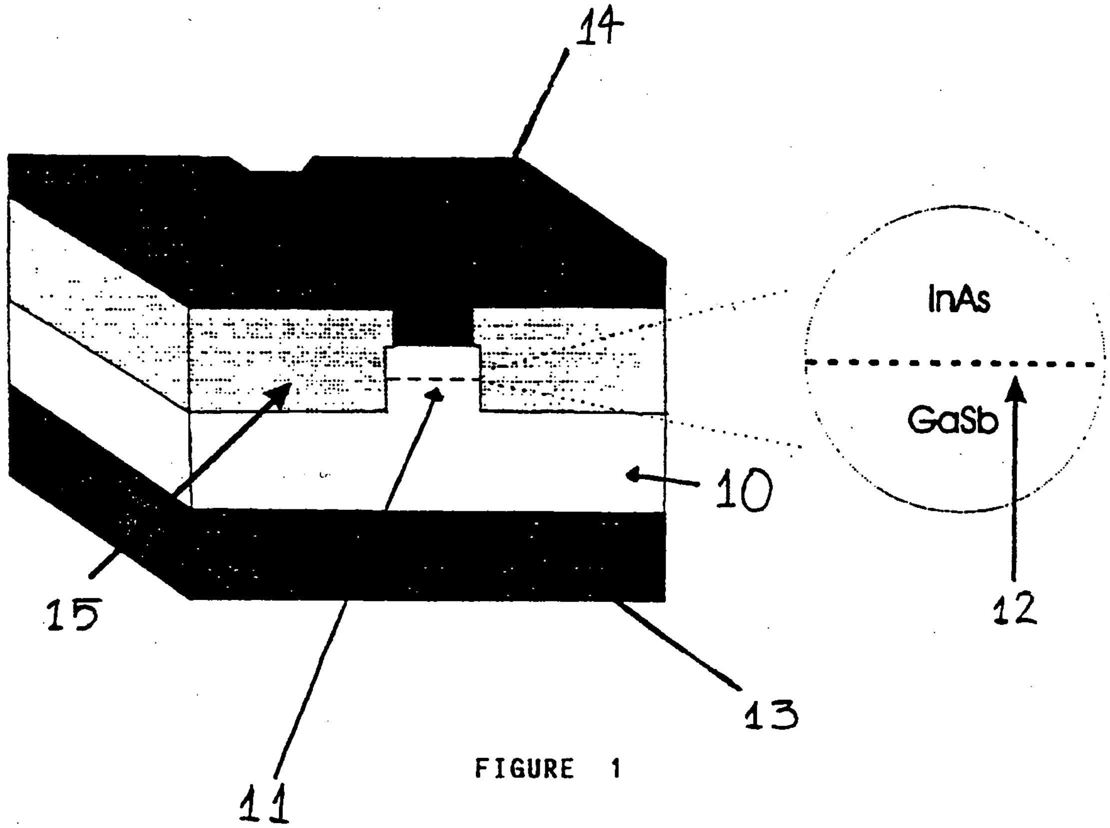


FIGURE 1

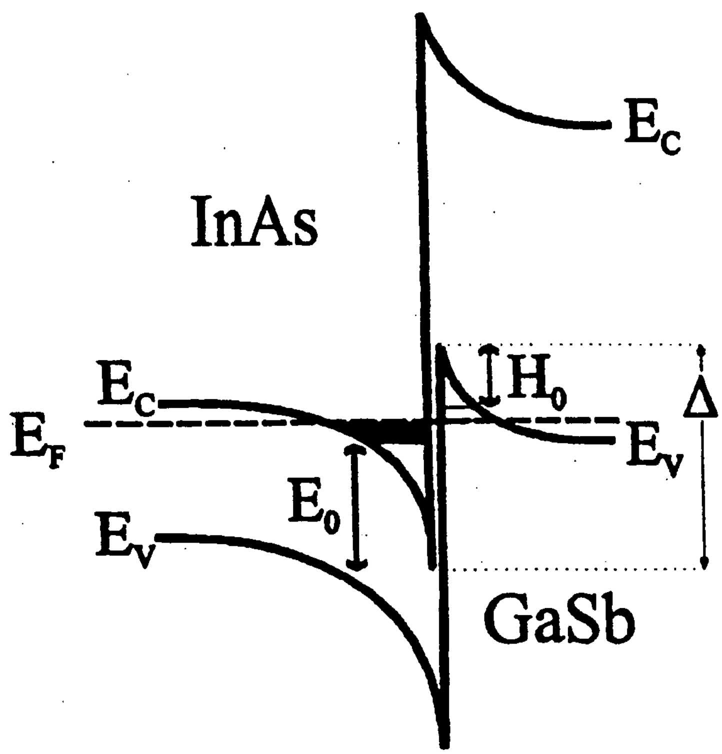
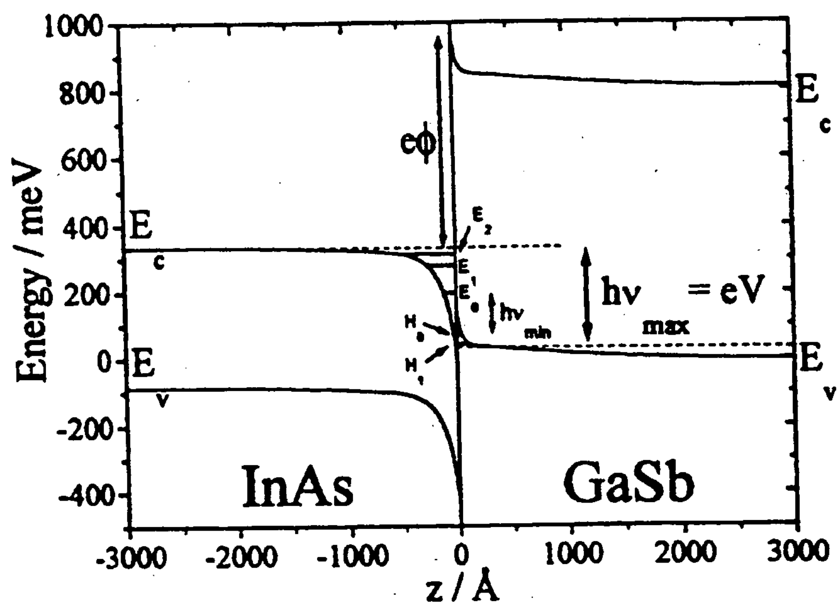


FIGURE 2a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H
1
hν
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= eV
InAs
GaSb
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-2000
-1000
0
1000
2000
3000
z / Å

FIGURE 2b

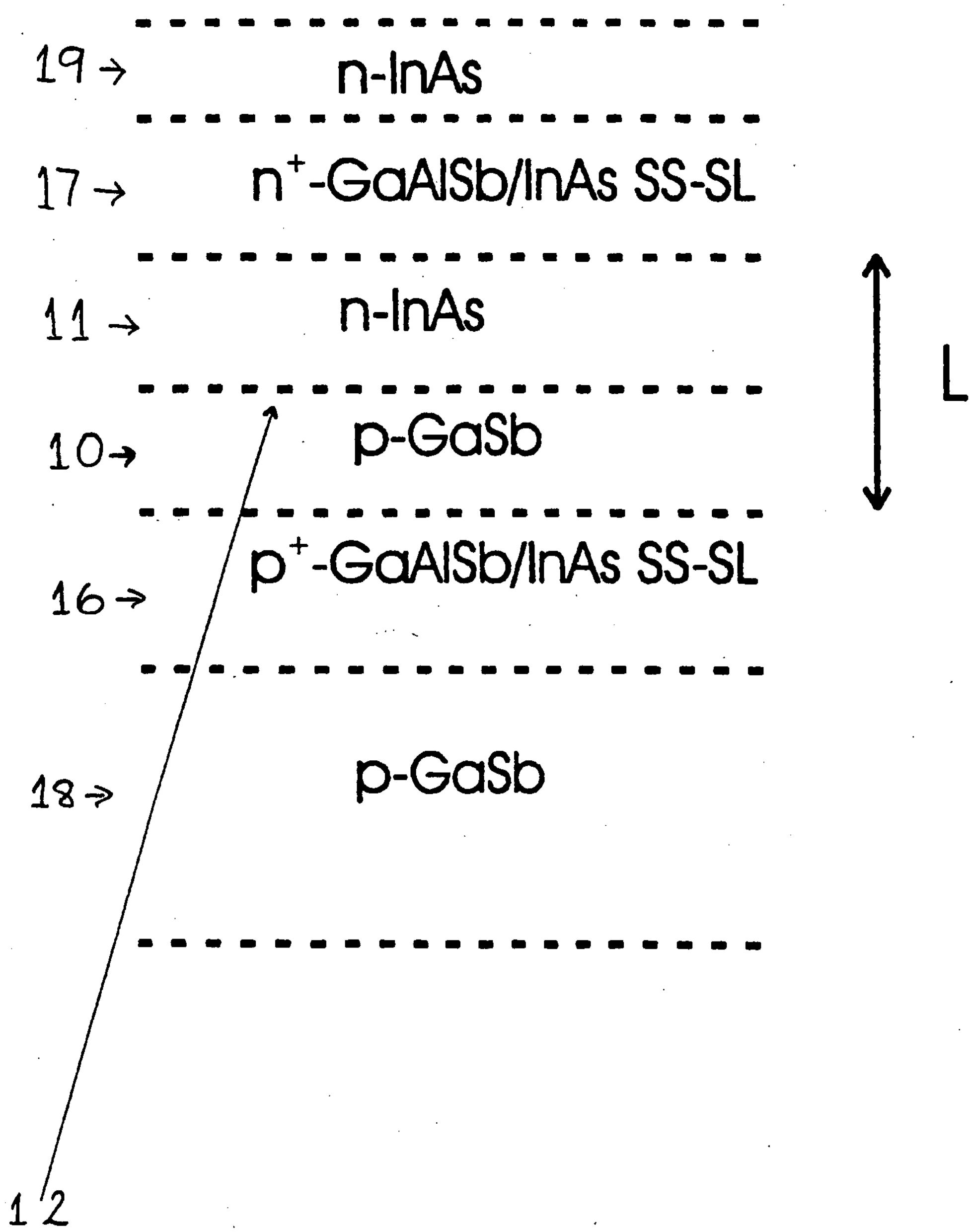
19 →
n-InAs
17 →
n+-GaAlSb/InAs SS-SL
11 →
n-InAs
L
10 →
p-GaSb
16 →
p+-GaAlSb/InAs SS-SL
18 →
p-GaSb
12

FIGURE 3a

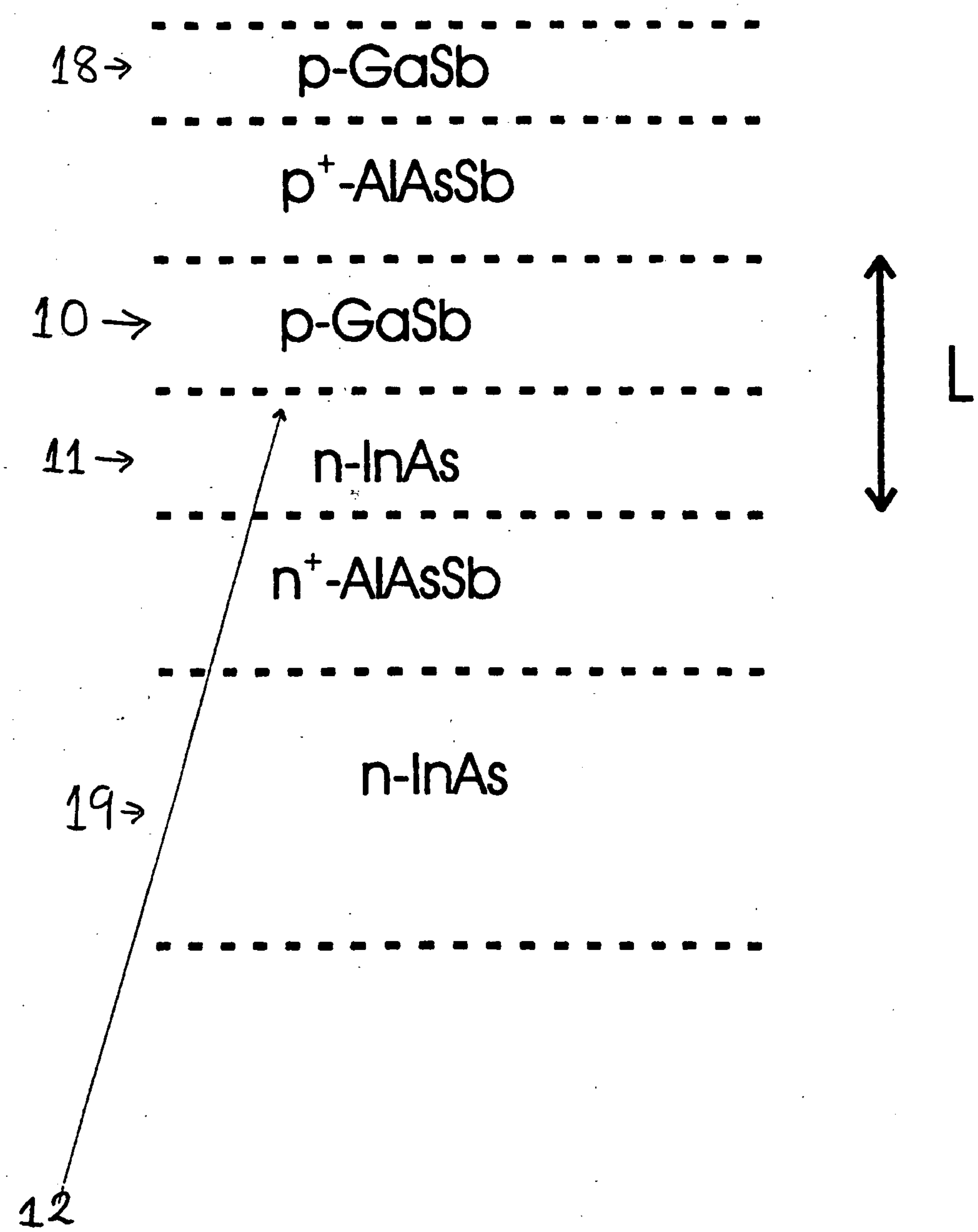

FIGURE 3b

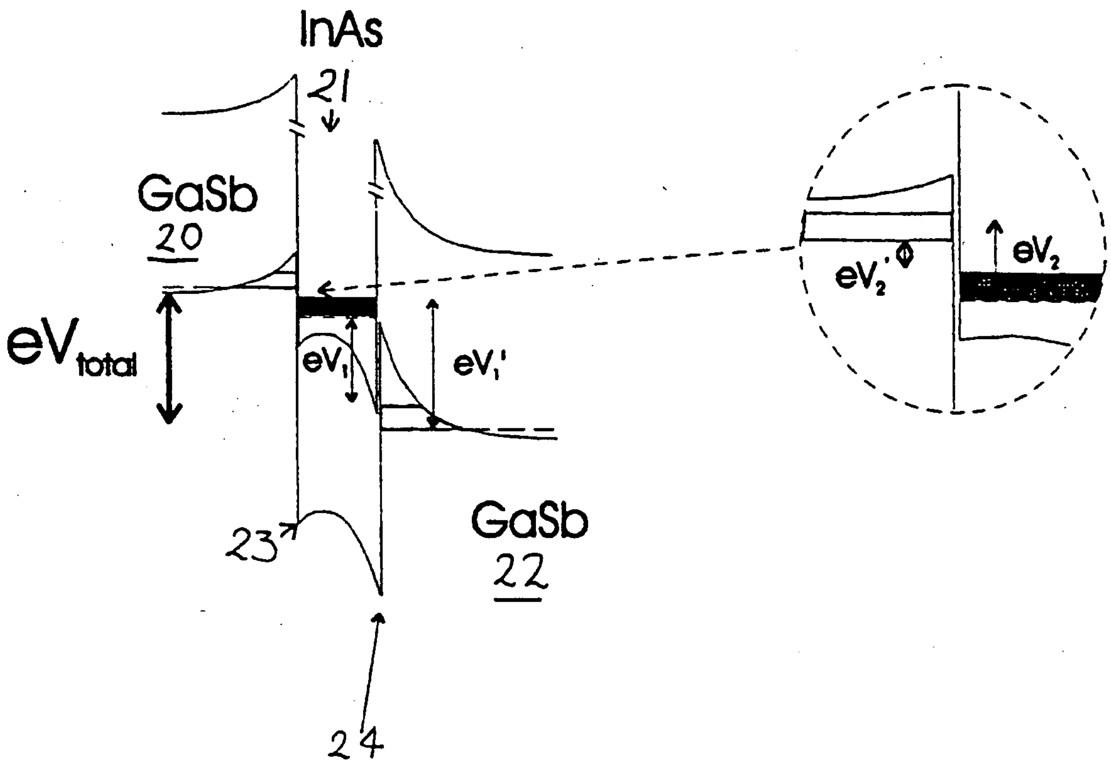

FIGURE 4a

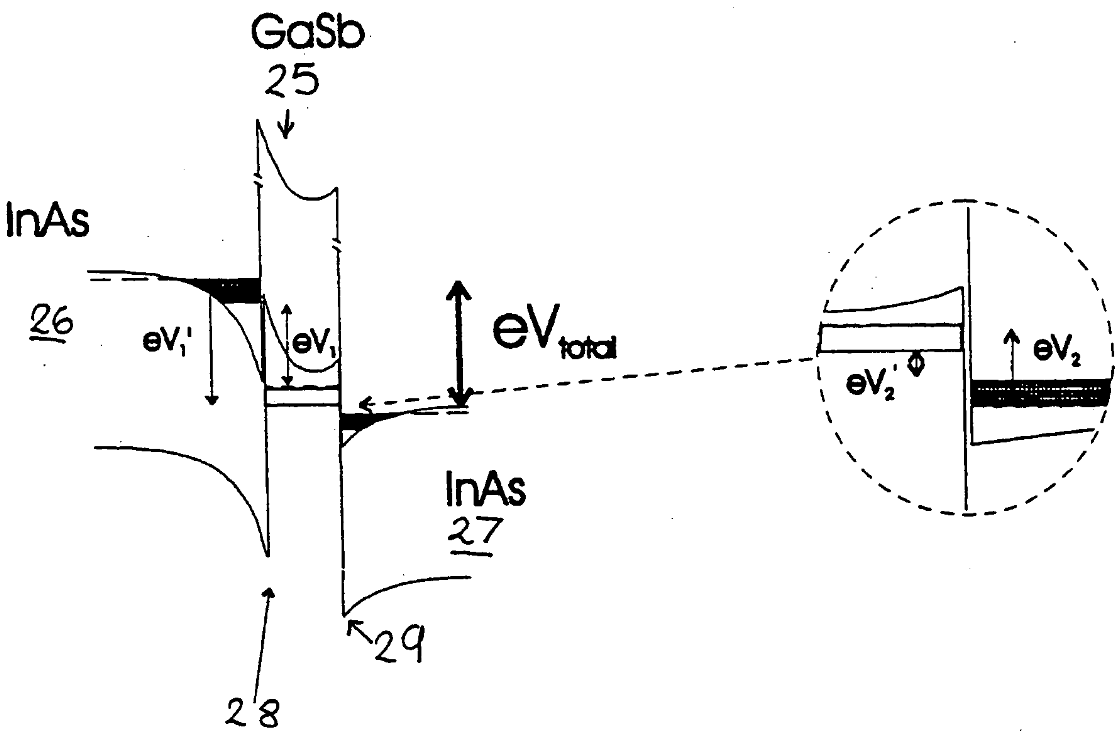

FIGURE 4b

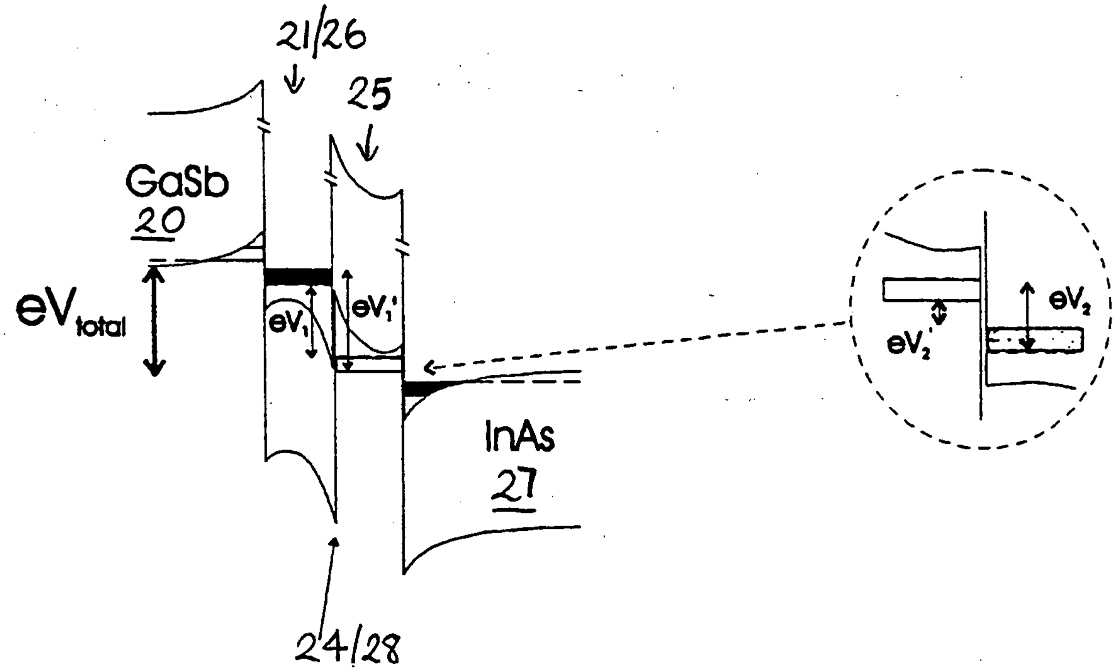

FIGURE 5

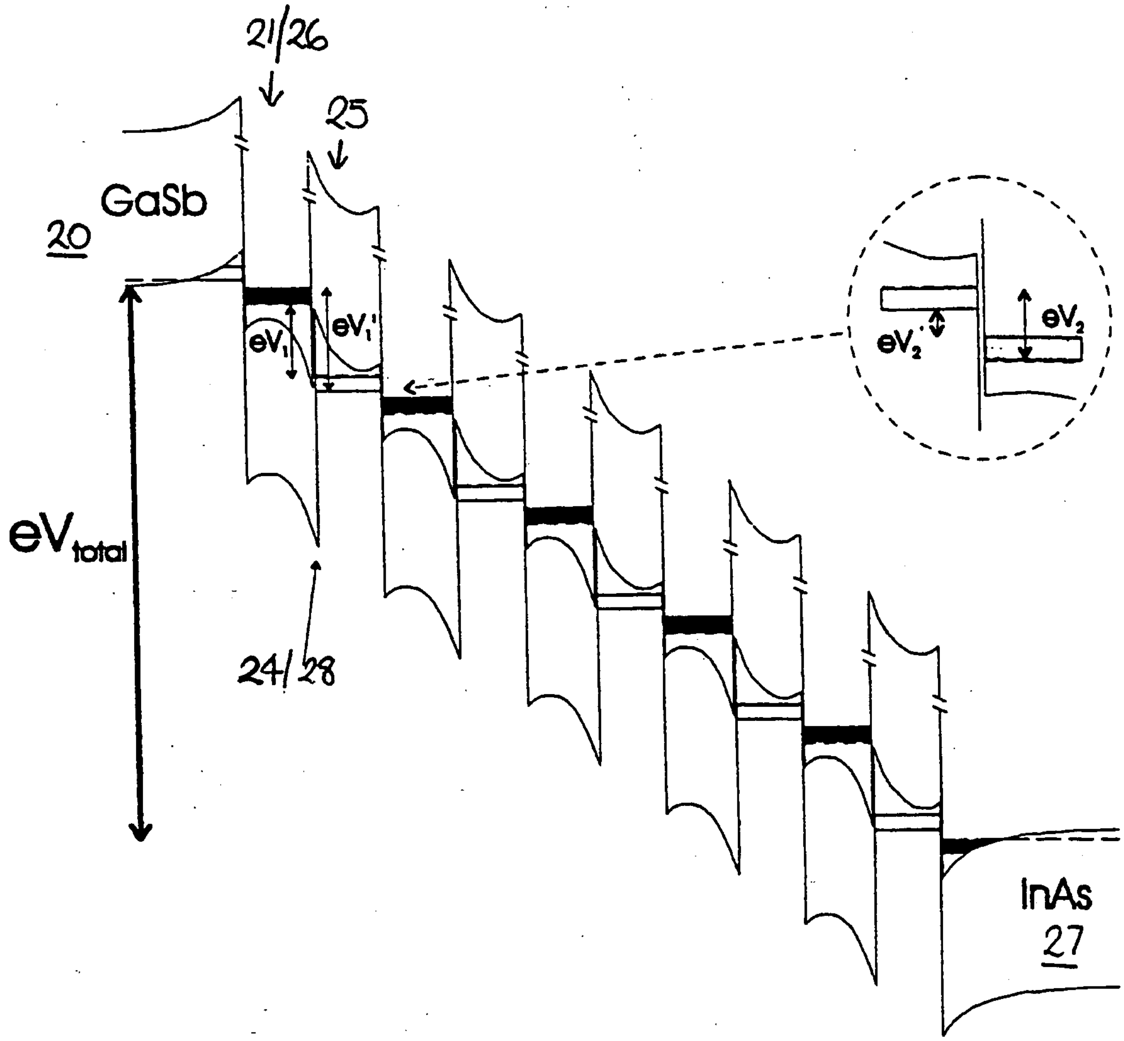

FIGURE 6

INTERNATIONAL SEARCH REPORT

Inter. onal Application No
PCT/GB 98/00729

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01L33/00 H01S3/19

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 018, no. 545 (E-1617), 18 October 1994 -& JP 06 196808 A (SONY CORP), 15 July 1994, see abstract --- -/--	1,7

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
3 July 1998	23/07/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	De Laere, A

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Inter. ›nal Application No
PCT/GB 98/00729

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	MIKHAILOVA M P ET AL: "Type II heterojunctions in GaSb-InAs solid solutions: physics and applications" PHYSICAL CONCEPTS OF MATERIALS FOR NOVEL OPTOELECTRONIC DEVICE APPLICATIONS I: MATERIALS GROWTH AND CHARACTERIZATION, AACHEN, GERMANY, 28 OCT.-2 NOV. 1990, vol. 1361, pt.2, ISSN 0277-786X, PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, 1991, USA, pages 674-685, XP000236450 see the whole document ---	1,3
A	PATENT ABSTRACTS OF JAPAN vol. 016, no. 227 (E-1207), 26 May 1992 -& JP 04 042983 A (FUJITSU LTD), 13 February 1992, see abstract ---	1
A	KLIPSTEIN P C ET AL: "Controlled growth of interfaces in InAs/GaSb heterostructures: their structural, vibrational and electronic properties" SEMICONDUCTOR HETEROEPITAXY. GROWTH, CHARACTERIZATION AND DEVICE APPLICATIONS, PROCEEDINGS OF SEMICONDUCTOR HETEROEPITAXY: GROWTH CHARACTERIZATION AND DEVICE APPLICTIONS, MONTPELLIER, FRANCE, 4-7 JULY 1995, ISBN 981-02-2479-6, 1995, SINGAPORE, WROLD SCIENTIFIC, SINGAPORE, pages 515-522, XP002070299 see abstract; figures ---	1,2,4,5
A	KHAN-CHEEMA U M ET AL: "High pressure studies of negative differential resistance in InAs/GaSb resonant conduction heterostructures" 6TH INTERNATIONAL CONFERENCE ON HIGH PRESSURE SEMICONDUCTOR PHYSICS, VANCOUVER, BC, CANADA, 21-24 AUG. 1994, vol. 56, no. 3-4, ISSN 0022-3697, JOURNAL OF THE PHYSICS AND CHEMISTRY OF SOLIDS, MARCH-APRIL 1995, UK, pages 463-467, XP002070300 see the whole document ---	1,2,4,5
A	US 5 588 015 A (YANG RUI Q) 24 December 1996 cited in the application see abstract; figures -----	1,11

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Interi .nal Application No

PCT/GB 98/00729

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5588015 A	24-12-1996	NONE	